N71-19946

NASA TECHNICAL MEMORANDUM

NASA TM X-2230

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COMPARISON OF AUTOMOTIVE THERMAL REACTORS ON A V-8 ENGINE

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • MARCH 1971

1. Report No. NASA TM X-2230	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle COMPARISON OF AUTOMOTIVE THERMAL REACTORS ON A V-8 ENGINE		5. Report Date March 1971
		6. Performing Organization Code
7. Author(s) Robert R. Hibbard, Cleveland O'Neal, William E. Riewaldt, and Alfred W. Young		8. Performing Organization Report No. E-6081
9. Performing Organization Name and Address Lewis Research Center National Aeronautics and Space Administration Cleveland, Ohio 44135		10. Work Unit No. 129-01
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		13. Type of Report and Period Covered Technical Memorandum
		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

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17. Key Words (Suggested by Author(s))	18. Distribution Statement
Manifold thermal reactor Automotive emissions Emission control systems	Unclassified - unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	14	$3.00

*For sale by the National Technical Information Service, Springfield, Virginia 22151

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SUMMARY

Two exhaust manifold thermal reactors, one experimental and one of proven design, were compared with a standard-manifold - secondary-air system for the control of hydrocarbon and carbon monoxide emissions. Tests were run at various speeds and loads on an unmodified V-8 engine that operated at relatively lean (high air to fuel ratio) conditions. Under these lean conditions there was little difference in the effectiveness of the three systems, and none approached the requirements for hydrocarbon control proposed for 1975. The reason is that, except at one high load condition, both reactors operated at temperatures well below the 1000 K (1340° F) that kinetic analysis suggests as a minimum operating temperature. A few tests were also run with one of the reactors using enriched (lower air to fuel ratio) carburetion. Very low concentrations of hydrocarbons were found under these conditions.

INTRODUCTION

The exhaust manifold reactor, often called the thermal reactor, is one of the systems that shows promise in reducing the concentrations of carbon monoxide and hydrocarbons in the exhaust of spark ignition engines. This is a noncatalytic mixer and reactor that replaces the conventional exhaust manifold. In it the carbon monoxide and hydrocarbons, along with the innocuous hydrogen, may be almost completely oxidized to water and carbon dioxide. Air must be added to the exhaust ahead of the reactor to provide an overall lean mixture, and the engine fuel-air ratio and timing must be modified to give the best cleanup of the exhaust. When this is done, the emission control is quite good and may meet the projected 1980 emission goals (ref. 1) for carbon monoxide and hydrocarbons (ref. 2). Nitrogen oxides are also reduced to a much lower level than found in uncontrolled cars and may also meet 1980 requirements; the future nitrogen oxide limits are less clear than those for the other pollutants.

However, the thermal reactor is effective only when operated at high temperatures and, in its present state of development, can run with metal temperatures up to 1325 K (1922° F). These temperatures present very serious materials problems, and reactor life may be quite short, especially if the reactor is made from low-cost ferrous alloys. The reactor also requires that the engine be run quite rich at low speeds for best cleanup of the pollutants, and this reduces fuel economy. Finally, and again in their present state of development, the reactors are large enough and have external surface temperatures hot enough so that they present installation and maintenance problems under the hood.

The biggest immediate problem in the thermal reactor system is that of finding or developing a high-temperature material that will give adequate life, hopefully for 100 000 miles of operation. The nickel-rich superalloys probably cannot be used because of the limited supply of nickel. Therefore, the National Air Pollution Control Administration (NAPCA), an agency of the Department of Health, Education, and Welfare, asked the NASA Lewis Research Center for help in seeking new materials and fabrication techniques that promise long-lived and low-cost reactors. A contracted program on materials is now being funded by NAPCA and managed by the Lewis Research Center.

The materials problems, along with those of poor fuel economy and underhood congestion, might be eased by new design. For this reason Lewis has started a small in-house program on combustion, fluid flow, and reactor design. The first results of this effort are an analysis of the chemical kinetics of carbon monoxide afterburning and the finding that a minimum temperature of about 1000 K (1340° F) will be required (ref. 3). Lewis has also started work on the thermodynamics of the internal combustion engine, and preliminary results are given in reference 4.

As part of this in-house program, the Lewis Research Center has installed an engine-dynamometer system to test materials and design concepts. The engine is a 1969 V-8 that has air injection into its exhaust ports as part of its standard emission control equipment. We have determined the hydrocarbon and carbon monoxide emissions from one thermal reactor of our own design and from one that represents the present state of the art in industry (ref. 2). These have been compared with the emissions from the engine run with and without its factory air injection. While most of the tests were run with the carburetor at its factory sitting, a few tests were made on the Lewis reactor with richer mixtures. Endurance tests have not been run nor have emissions been determined under simulated driving cycles. We have only determined performance at several engine speeds and loads. Reported herein are the results of these preliminary experiments.

APPARATUS AND PROCEDURE

Engine Installation

A 1969 model year, 472-cubic-inch- (7700-cm^3-) displacement V-8 engine with a factory-installed air injection system as shown in figure 1 was used for this investigation. The engine was directly coupled by a shortened standard drive shaft to a 300-horsepower (2240-W) dynamometer. The dynamometer was used as a motor to start the engine and then as a generator to absorb the energy produced by the engine. A shell and tube heat exchanger was used to maintain the thermostatically controlled glycol engine coolant temperature.

The air injection system consists of an air pump with cast-in-head distribution passages. The air pump delivered approximately 0.042 pounds (19 g) per minute per 100 engine revolutions per minute to each bank. The air system was modified so that the air to one engine bank could be cut off completely, or be maintained at half standard, standard, or twice standard flow rates.

The engine was operated at factory settings of carburetion and ignition timing. A few tests were made with enriched mixtures obtained by applying small pressures to the carburetor bowl vents. The engine was given a short break-in period, but no attempt was made to equilibrate combustion chamber deposits.

Test Conditions

Tests were run only at steady-state conditions with set values for engine speed and manifold vacuum. No attempt was made to simulate any driving cycle, any car-speed - road-load condition, or any transient conditions of warmup, acceleration, or deceleration. The same batch of leaded, premium-grade fuel was used for all the work.

Reactor Systems

Three emission control systems were tested. The first was the factory installed system and consisted only of the regular cast-iron exhaust manifold along with the in-head air injection.

The second system was an exhaust manifold reactor developed by, and purchased from, a company with considerable experience with these reactors. It was substantially the same as the type VI reactor of reference 2, specially tailored to our 472-cubic-inch- (7700-cm^3-) displacement engine. The air injection system came with the engine.

The third system was a manifold reactor designed and fabricated at the Lewis Research Center and sketched in figure 2. The overall dimensions and internal volume of this reactor were substantially the same as those of the second system. The design feature attempted was to promote mixing by using jets directed down the core and to avoid the direct impingement of gas against surfaces normal to the exhaust port. Runner tubes were shaped at one end to fit into the exhaust port and thereby decrease heat loss to the engine head. The other end of these tubes extended into and nearly all the way across the reactor core. The core end of these tubes was sealed off, and ports were machined in the sides to direct the gas axially down the core. The reactor core was made of type 304 stainless and insulated by a multiple wrap of dimpled stainless foil around the core. The outer can was mild steel.

Instrumentation

The instrumentation used for these tests is shown schematically in figure 1. The air injection flow rate to each engine bank was measured by rotameters. Thermocouples were used to sense the exhaust gas temperature at each reactor exhaust just upstream of the port where gas samples were taken off. Thermocouples were also used to sense the reactor core temperatures.

Nondispersive infrared analyzers (NDIR) were employed to determine components of interest in the exhaust gas. The system consisted of two NDIR's installed in a cabinet with a pump, flowmeters, filters, and associated valves. The hydrocarbon analyzer had two ranges, 0 to 500 ppm and 0 to 2500 ppm. Carbon monoxide was determined with the second analyzer, whose range was 0 to 10 percent. Samples were taken from a single point as shown in figure 1.

RESULTS

The three emission control systems were tested under several engine conditions. Most tests were run on an engine having the factory settings of carburetion and timing. This engine runs quite lean, and it has been well established that the thermal reactor gives the best control of emissions when the engine is operated rich (ref. 2). This is because a rich engine exhausts relatively large amounts of carbon monoxide, hydrogen, and hydrocarbons, and the afterburning of these fuel components raises the temperature of the exhaust gas and promotes the combustion processes that clean up the exhaust.

The engine was run long enough at each condition to stabilize the exhaust gas composition and reactor core temperature. The carbon monoxide and hydrocarbon emissions and the reactor temperature for each of the three emission control systems at each test condition are shown in table I. The standard output of the air injection system was used. Also shown are the emission with the air cut off to the standard manifold.

The following observations are made regarding the data in table I:

(1) There was little difference between the two reactors, and neither was significantly better than the standard exhaust manifold system in the control of either the carbon monoxide or the hydrocarbons. At the lower engine speed conditions the plain exhaust manifold gave lower emissions than either reactor and at higher speeds the reverse was generally true. But none of the three systems showed a clear advantage over the other two at any single condition or overall.

(2) Except for the lowest speed, the carbon monoxide emissions were very low even with no added air. This shows that the engine carburetion was set quite lean for all but the lightest load conditions.

(3) Except for the heaviest load condition, number 12, the hydrocarbon emissions were all well above those obtained by others who have tested thermal reactors (e.g., ref. 2).

(4) The reactor core temperatures were below 1000 K (1340° F) for all but the heaviest load condition. The significance of this is discussed in the next section.

We also ran a second series of tests in which the rate of injected air was varied. This air system had been modified and rotameters installed so that the air could be injected at the standard rate and at about half standard and twice standard rates. The concentrations of carbon monoxide and hydrocarbons in the exhaust were corrected for differences in dilution by normalizing to the standard rate condition. The results for the hydrocarbons only are shown in table II, and the values for the standard air rate are repeated from table I.

Inspection of table II shows no significant difference in the hydrocarbon emissions as the rate of air injection was varied. The two thermal reactors again showed no significant improvement over the engine's standard manifold system at any of the three air injection rates and, except at the heavy load condition 12, the concentrations ran well above those published elsewhere.

Carbon monoxide (CO) data were also obtained with half and twice standard air injection rates. However, after correcting for dilution, the level of CO emissions was substantially identical with those shown in table I. These CO data are not presented herein.

The effect of carburetor enrichment on the performance of the Lewis designed reactor is shown in table III. At each of the three conditions listed, the carburetor bowl vents were slightly pressurized with air to increase the fuel to air ratio. The resulting ratio could not be estimated because there was insufficient instrumentation, but the qualitative trend towards richer mixtures is clearly shown by increased CO concentrations as measured with the secondary air turned off.

It can be seen that the hydrocarbon levels are greatly reduced with increasing fuel to air ratio and down to the levels of about 10 ppm reported for other thermal reactors in references 2 and 5. The CO and hydrocarbon concentrations shown for "normal" carburetion in table III differ somewhat from those shown for the same test conditions in table I. However, these tests were run at different times and with probably inadvertent changes in engine tuning. The temperatures (metal) of the reactor core also increased as the fuel to air ratio increased, as shown in table III.

DISCUSSION

With normal (lean) carburetion neither reactor reduced the hydrocabon emissions to anywhere near the level that may be required for 1975 and later year cars. Furthermore, the performances of both reactors were no better than that obtained with the standard exhaust manifold, an uninsulated system with much less internal volume than the reactors.

Thermal reactors require some carburetor enrichment, especially over the low-speed and light-load portion of the metering range. The good results reported for reactors have been obtained with carburetion that has been so modified (refs. 2 and 5) and are confirmed by the results presented herein for the Lewis designed reactor.

The need for carburetor enrichment to get good thermal reactor performance is almost certainly a temperature requirement. The chemical kinetics require a minimum temperature for afterburning reactions, as shown by the analysis of Brokaw and Bittker (ref. 3). Figure 3 is reproduced from their report and shows that a minimum temperature of about 1000 K (1340° F) is required for a reasonably complete oxidation of CO in times of the order of 10 to 20 milliseconds. The residence times of exhaust gases in a typical reactor vary with engine conditions and are in the 5 to 50-millisecond range. Figure 3 shows the rates to be much lower at 900 K (1160° F) and much faster at 1100 K (1520° F). In general, temperatures above about 1000 K (1340° F) appear necessary to give good thermal reactor performance in the afterburning of CO. It is believed that the oxidation of hydrocarbons will be rapid when CO is rapidly oxidized and slow when the CO oxidation is slow. It can be seen in table I that the reactor core temperatures were well below 1000 K (1340° F) except for the high-load condition (12), and for this reason the performance of both reactors was poor. Enriching the engine raises the reactor temperature by supplying to it an exhaust gas with considerable combustible content in form of CO, hydrogen, and, to a lesser extent, hydrocarbons. The combustion of these species maintains the reactor at a high enough temperature for effective afterburning.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, November 30, 1970,
129-01.

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TABLE I. - PERFORMANCE OF EMISSION CONTROL SYSTEMS WITH STANDARD AIR INJECTION RATES

Test conditions			Carbon monoxide, percent				Hydrocarbons, ppm C_6				Core temperature, K (^oF)	
Condition	Engine speed, rpm	Manifold vacuum, in. Hg (torr)	Standard manifold		Industry reactor with air	Lewis reactor with air	Standard manifold		Industry reactor with air	Lewis reactor with air	Industry reactor	Lewis reactor
			No air	With air			No air	With air				
1	600	20 (508)	3.10	0.60	0.95	0.95	275	65	180	75	----------	717 (830)
2	600	18 (468)	1.60	.25	.60	.90	240	95	110	120	777 (940)	717 (830)
3	1000	20 (508)	.75	.25	.25	.40	245	100	100	105	----------	765 (915)
4	1000	18 (468)	.40	.25	.40	.30	240	135	180	170	----------	777 (940)
5	1000	16 (408)	.20	.15	.25	.20	230	155	200	190	864 (1095)	794 (970)
6	1400	20 (508)	.30	.15	.30	.30	180	90	75	75	----------	839 (1050)
7	1400	18 (468)	.15	.10	.15	.20	175	115	110	90	----------	850 (1070)
8	1400	16 (408)	.10	.10	.10	.15	175	125	170	105	941 (1235)	875 (1115)
9	1800	20 (508)	.15	.15	.10	.20	45	60	45	50	----------	883 (1130)
10	1800	18 (468)	.10	.10	.10	.20	120	75	60	60	----------	900 (1160)
11	1800	16 (408)	.10	.10	.10	.15	130	100	70	70	975 (1295)	918 (1190)
12	2000	10 (254)	----	----	.40	.15	---	---	15	30	1147 (1605)	1102 (1525)

TABLE II. - EFFECT OF AIR INJECTION RATE ON HYDROCARBON EMISSIONS

Test conditions				Hydrocarbons, ppm C_6					
Condition	Engine speed, rpm	Manifold vacuum, in. Hg (torr)	Standard manifold, standard air	Industry reactor			Lewis reactor		
				Standard air	Twice standard	Half standard	Standard air	Twice standard	Half standard
1	600	20 (508)	65	80	90	85	75	90	72
2	600	18 (468)	95	110	101	103	120	124	112
3	1000	20 (508)	100	100	112	108	105	118	111
4	1000	18 (468)	135	180	169	198	170	169	175
5	1000	16 (408)	155	200	191	202	190	197	191
6	1400	20 (508)	90	75	79	81	75	84	72
7	1400	18 (468)	115	110	112	112	90	101	99
8	1400	16 (408)	125	120	124	117	105	118	108
9	1800	20 (508)	60	45	51	34	50	62	45
10	1800	18 (468)	75	60	62	54	60	67	54
11	1800	16 (408)	100	70	71	63	70	82	61
12	2000	10 (254)	---	15	17	30	30	34	36

TABLE III. - EFFECT OF CARBURETOR ENRICHMENT ON

EMISSIONS FROM LEWIS DESIGNED REACTOR

Test condition	Carburetion	Without secondary air	With secondary air			
		Carbon monoxide, percent	Carbon moxide, percent	Hydrocarbon, C_6, ppm	Core temperature	
					K	^{o}F
3(1000 rpm, 20 in. Hg (508 torr))	Standard	0.75	0.2	80	760	908
	Enriched	4.6	1.3	65	814	1005
	↓	6.1	.6	30	943	1238
	↓	10.0	.6	10	1040	1412
7(1400 rpm, 18 in. Hg(468 torr))	Standard	0.1	0.1	60	818	1013
	Enriched	.7	.25	40	840	1053
	↓	2.6	.6	15	863	1093
	↓	5.8	.05	5	1020	1377
11(1800 rpm, 16 in. Hg (408 torr))	Standard	0.15	0.1	60	873	1112
	Enriched	.1	.1	50	893	1148
	↓	1.2	.3	20	924	1204
	↓	6.7	.3	10	1016	1370

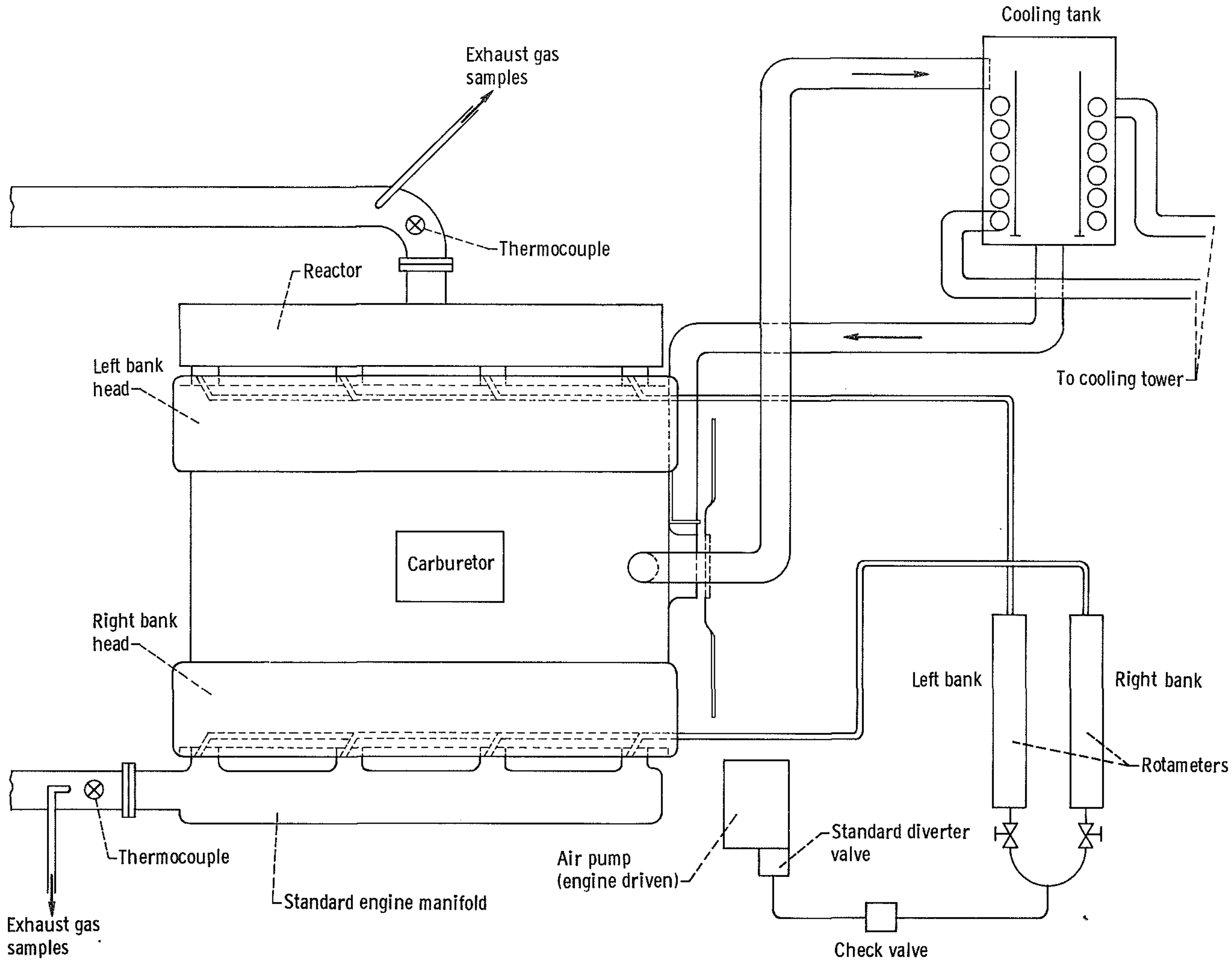

Figure 1. - Engine equipment arrangement.

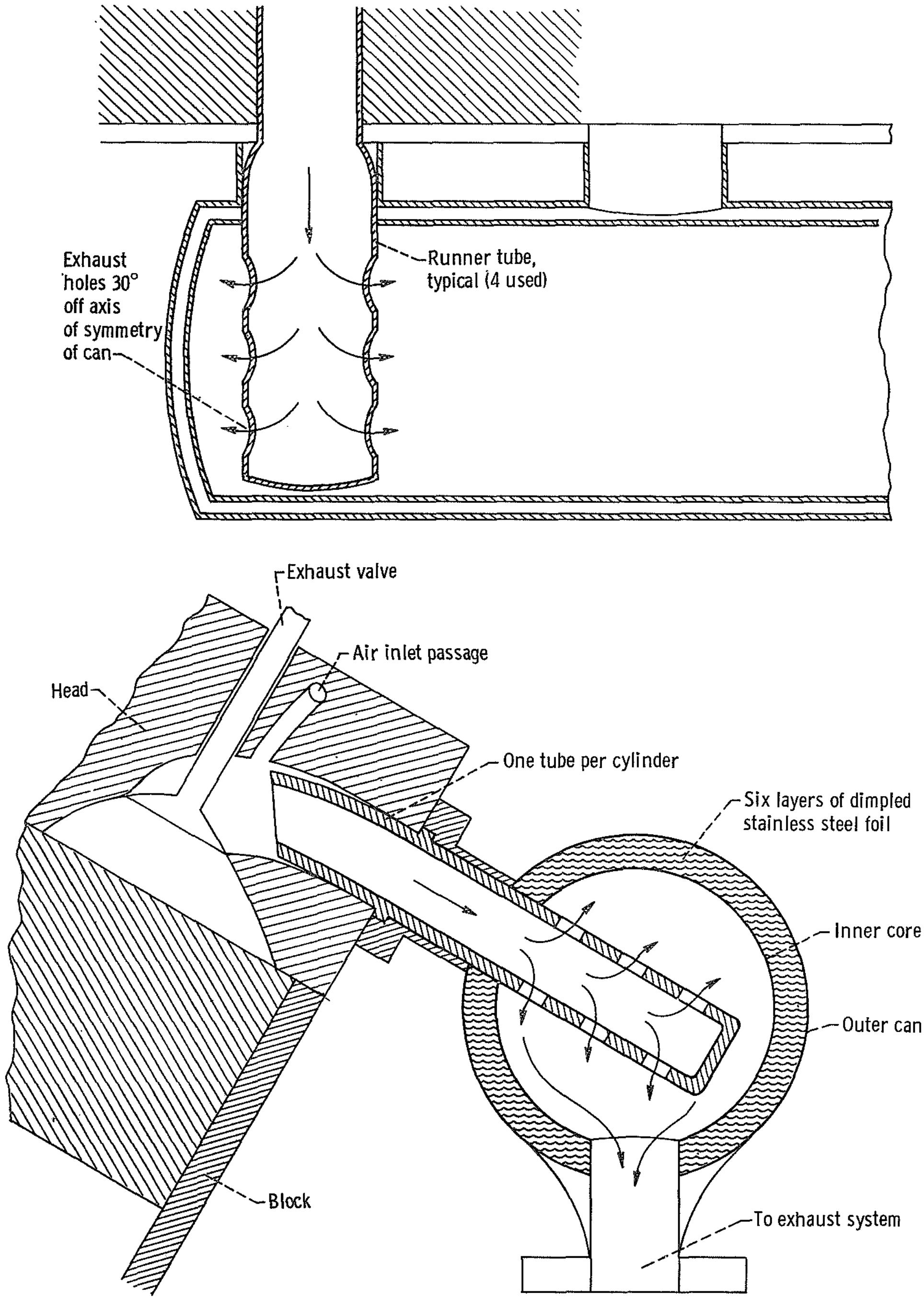

Figure 2. - NASA Mark I reactor.

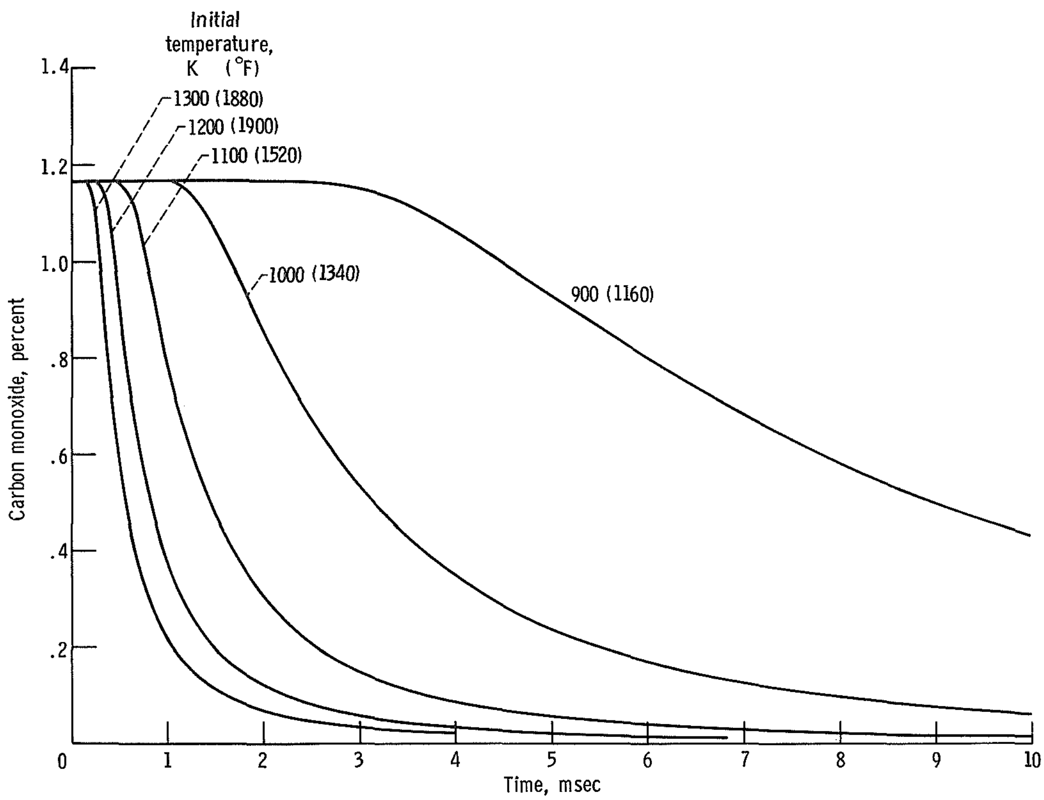

Figure 3. - Carbon monoxide concentration as function of time. Initial air-fuel ratio of 14 (cruise condition) diluted to 17 (lean).

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